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ANALYSIS OF STRUCTURAL AND NONSTRUCTURAL FLOOD CONTROL MEASURES USING COMPUTER PROGRAM HEC-5C

WILLIAM K. JOHNSON AND DARRYL W. DAVIS

NOVEMBER 1975



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stage-damage, discharge-damage, and damage frequency relationships. Diversion and flood forecasting affected these relationships the least, but all the methods affected the damage frequency. The HEC-5C program was used to develop systems which maximize net economic benefits. Given an existing system and an array of flood control measures, the strategy proceeds by computing expected annual damages for the existing system; adding any one of the flood control measures and computing expected annual damages; then subtracting expected annual damages with or without the control measure. Finally, the best measure was chosen based upon its final net benefit yield. A final added strategy recomputed costs and benefits by removing one of the control measures to determine if a better net benefit figure would be yielded. The Fall River System of California was used to illustrate how the program functions.

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William K. Johnson and Darryl W. Davis

November 1975

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AHALYSIS OF STEUCTURAL AND HOMSTRUCTURAL FLOOD CONTROL MEASURES USING COMPUTER PROCPAR MEC-50

by William K. Johnson and Darryl W. Cavis

INTRODUCTION

This training document is intended to illustrate how a variety of structural and nonstructural flood control measures can be analyzed using computer program HEC-5C, "Simulation of Flood Control and Conservation System." Originally developed in 1973 by Pill S. Eichert, the program has undergone several significant changes to make it a more useful tool in the formulation and assessment of flood control systems. A major addition was the development, by Darryl Davis and Harold Kutik, of an economic routine to compute average annual damages at specified damage centers within the system. This in turn leads to damages reduced or inundation reduction benefits. Its full computational capabilities are described in references 1 and 2.

This document is divided into three parts and illustrates how this model can be used in planning to formulate and assess alternative systems of both structural and nonstructural measures. The first part is a discussion of some basic principles of flood control planning; part II illustrates the application of many of the principles described in part I; the third part contains supportive computer output developed as part of the application in part II.

PART I

FLOOD CONTROL AND DAMAGE REDUCTION

A variety of flood plain management measures are available to reduce flood damage. Their primary purpose is to protect damageable property, both existing and future, and they do this in one of two ways. Either they are designed to control the hydrology, that is, the magnitude or frequency of flooding, or they are designed to reduce the susceptibility of property to damage. The tabulation below shows typical measures of each type (see also reference 5).

Flood Plain Management Measures

Those Designed to Control the Hydrology	Those Designed to Reduce the Susceptibility of Property to Damage
Reservoirs	Flood Proofing
Levee or Floodwall	Relocation
Channel Modification	Flood Marning
Diversion	
Flood Forecasting	

Measures designed to alter the hydrology, either locally or throughout a system, can alter various hydrologic relationships which exist at specific locations. Similarly, measures designed to modify the susceptibility of property to damage can, through the protection they provide, alter economic relationships which exist. Because both hydrologic and economic relationships are used to compute the magnitude of damage

caused by inundation, it is important to understand what these relationships are, and how they can be altered by the various measures.

Hydrologic and Economic Relationships

Stage-Discharge Relationship (Figure 1)

This is a basic hydraulic function which has many uses in water resources engineering. In river channels or flood plains it expresses, for a specific location, the fact that under most conditions, as the river stage increases, the river discharge increases.

Stage-Damage Relationship (Figure 3)

This is the economic counterpart to the stage-discharge function and represents, at a specific location, the magnitude of dollar damages which may occur in a river reach, at a given river stage. Usually the damages represent an aggregate of damages which occur some distance upstream and downstream from the specified location.

Discharge-Damage Relationship (Figure 4)

Stage is a common parameter to both the stage-discharge and stagedamage functions and as such may be used to develop a function relating discharge to damage.

Discharge-Frequency Relationship (Figure 2)

Using historic streamflow records, the exceedance frequency of various magnitudes of annual peak flow can be estimated using statistical techniques. Because exceedance frequency expresses the frequency with which certain events occur over time it is used for computing damages

on an average annual basis, and for determining the degree of protection and risk of various measures. It is developed for a specific location in the system.

Damage-Frequency Relationship (Figure 5)

The common parameter in both the discharge-damage and discharge-frequency relationships is river discharge. By selecting a range of discharges a function relating damages to exceedance frequency can be developed. The integration of this function, that is, determining the area beneath a graphical representation of the function, is the expected annual damages at that location. When various measures are considered in planning the reduction in damages is measured as the difference between the expected annual damages without the measures (existing conditions) and the expected annual damages with the flood control measures in place (modified conditions). Any changes which occur in the stage-discharge, stage-damage, or discharge-frequency relationships will be reflected in the damage-frequency function, and therefore in the magnitude of the expected damage reduction.

Generally, from a national viewpoint, the economic benefits of implementing flood control measures are the economic contributions which result from improving the net productivity of flood-prone land. This improvement may come about by reducing damages to the land under its present and anticipated future use, by allowing for more intensive use, and by attracting new uses. Detailed principles and procedures for computing these benefits are discussed in reference 4. The hydrologic and economic

relationships discussed previously are used to compute damage reduction which is the economic benefit resulting from preventing inundation. Throughout this document economic benefit refers to the damage reduction benefit.

Effects of Flood Control Measures

Reservoirs

The function of a flood control reservoir is to store flood waters during storm periods and release them during periods of lower flow. Decause the flow of the stream upon which the reservoir is located is interrupted, the flood frequency at all locations downstream can be altered, that is, the magnitude of flow can be reduced for a given frequency of event. The magnitude of this flow reduction may be small or large depending upon the size of the reservoir, the magnitude and centering of the storm, and the location of the reservoir in relation to the downstream point. Upstream from the reservoir, the streamflow remains unaltered except for any backwater effect which may exist where the stream enters the reservoir pool. A discharge-exceedance frequency relationship at a point immediately downstream would be altered to reflect lower flows for a given exceedance frequency, or alternately for a given magnitude of flow the occurrence is less frequent. This is the direct hydrologic effect of controlling the flow. The economic effect is a reduction in expected annual flood damages brought about by a lessening of the expected magnitude and frequency of flooding.

Because reservoirs can be operated to make releases at desired times, locations and in desired amounts their effect can extend beyond immediate downstream points to other locations in the system. This influence, or system effect, can take many forms, for example,

Timing - the timing of flood peaks at a particular location can be affected with reservoir regulation. Peaks may be made to occur before, after or coincident Jepending upon operating criteria.

Location - Reservoirs in a system usually operate to reduce flooding at one or more locations. When one location is removed, by providing flood control through some other measure, for example, relocation, it allows the reservoir to operate more effectively for those locations remaining.

Magnitude - The magnitude of flow released from one reservoir in a system influences how much is released from the others and can therefore influence the flood storage remaining.

Levees and Floodwalls

Levees and floodwalls are designed to prevent flooding in areas adjacent to a river or flood plain. They provide a direct means of flood protection in that they can be located where needed and can act to confine flood waters to the channel up to the design discharge. In cases where the levee or floodwall prevents flood flows from occupying areas in the flood plain or channel that normally would be occupied, the river stage will be higher for a given flow. This is caused by a

reduction in cross-sectional area available to carry the flood flow.

Downstream, higher flood peaks can occur because valuable flood plain storage was eliminated upstream increasing the concentration of runoff. So while levees and floodwalls have the local effect of increasing the height of the channel's sides and reducing flooding at that location, they can, at the same, have the system effect of increasing flooding downstream.

These changes can alter the hydrologic and economic relationships which exist at a given location by raising the stage-discharge function (assuming less cross-sectional area for a given flow) and by truncating the lower portion of the stage-damage function (assuming no damages will occur below the top of the levee or floodwall). If the reduction in flood plain storage is substantial this could alter the discharge-frequency function downstream, much in the way reducing the storage in a small unregulated reservoir would. The magnitude of these changes depends upon the specific circumstances.

Channel Modifications

Channel modifications are usually designed to increase the carrying capacity of a reach of river. This is often accomplished by increasing the cross-sectional flow area by enlarging the channel; decreasing surface roughness by clearing and snagging or lining the channel; and reducing the energy loss by straightening a channel reach. All of these actions are aimed at passing flows more efficiently, that is, the conveyance area is reduced and velocity increased, resulting in a lowering of river stage

for a given flow, and therefore altering the stage-discharge function. Downstream from the channel modification the magnitude of flow may be greater than without the modification, that is, the magnitude of flow may increase for a given exceedance frequency event. This occurs because the lowering of stage upstream causes less water to be stored in the channel, thus the attenuation effect is less, which again is analogous to the storage effect of reservoirs - less storage, less attenuation. Actual magnitudes of change depend upon the modification and length of river reach.

Diversion

A flow diversion is intended to take water out of the river during high stages and divert it away from the main channel. This has the immediate effect of reducing the amount of flow at all locations below the diversion either by decreasing the magnitude of flow or altering the timing in the case of return flow. At all points below the diversion, the discharge-frequency function will be altered - usually lowered - except where return flow coincides with peak flow in the main channel in which case the total channel flow could be higher than without the diversion. Therefore, two factors - magnitude of diversion and timing of return flow - can influence the manner in which the discharge frequency function is altered.

Flood Forecasting

Knowing in advance where and how much runoff will occur allows flood control measures, such as reservoirs and diversions, to be operated in a

manner such that flows are better controlled at critical damage centers, resulting hopefully, in lower damages than without forecasting. Knowing what flows to expect 12, 13, 24 hours in advance is better than taking them as they come. Knowledge of future flood events usually comes from a real-time flood forecasting network which includes rainfall and streamflow measuring equipment located throughout the basin with data fed into a central control which forecasts estimates of runoff and regulates reservoirs and diversions to minimize flood damage downstream. In terms of the hydrologic functions, the regulated discharge-frequency relationship downstream from reservoirs and diversions may be modified in that information which alters the operating decisions may result in different magnitudes of flow downstream. There would be no change in the stage-damage function.

Flood Proofing

As the name implies flood proofing is the protection of damageable property from flood waters. This usually means protecting individual structures and its contents. A variety of construction methods and materials are available to provide this protection, their use being determined by the type, location and susceptibility to damage of structure and contents. Then protection is provided and a structure or group of structures are 'flood proofed' the relationship between stage and damages is modified since it is expected that less damage will occur for a given stage, up to the elevation of flood proofing. How this function will look will depend upon the type and extent of flood proofing. The hydrology will remain unchanged unless the flood proofing measures

result in a significant change to the flow area. In the context of system operation the existence of flood proofing lessens the need for control at that location, thus operation can be focused on other locations with higher damage potential.

Relocation

From the standpoint of strictly preventing flood damage, relocation can be completely effective if the structures are moved to a location free of potential flood damages. By removing damageable property from areas susceptible to floods there is no need for control or protection and no damage occurs. Unfortunately, this is not always a feasible alternative, however, it does play an important role as an alternative in some cases. The effect of relocation is to modify the stage-damage function by removing damageable property. If all damageable property is removed there would be no expected damages, if only a portion of the damages were removed the function would be modified accordingly.

Flood Warning

A reasonable advance warning can allow temporary measures to be implemented to protect or remove damageable property. For example, the evacuation of movable property or the raising or sandbagging of property which must remain. Flood warning is a combination of flood proofing and evacuation, and while it is not as dependable as the permanent measures it can help to reduce potential damages. Only the economic functions are altered as described in the sections on flood proofing and evacuation.

Summary

A summary of the direct effects of all the measures on each of the hydrologic and economic relationships are shown below. Each relationship is assumed to be at or downstream of the respective measure, for example, for a reservoir the direct effect is downstream, for a levee it is at the site.

Direct Effects of Flood Plain Management Measures on Hydrologic and Economic Relationships

Hydrologic and Economic Relationships
(at or downstream from the measure for existing conditions) NC = No Change M = Modified

Measure	Stage- discharge	Stage-2/	Discharge- damage	Discharge _{3/}	Damage Frequency
Reservoir	NC	NC	NC	M	M
Levee or Floodwall	М	M	М	NC	M
Channel Modification	M	NC	М	NC	M
Diversion	NC	NC	NC	М	M
Flood Forecasting	NC	NC	NC	М	M
Flood Proofing	NC	M	М	NC	М
Relocation	NC	М	М	NC	M
Flood Warming	NC	M	М	NC	M

Where a reservoir or diversion significantly modifies the channel flow, deposition or erosion of channel material could alter the channel cross-section and thus the stage-discharge relationship. Also, removal or placement of damageable property in the floodplain could result in modifying the function.

^{2/} Along river reaches which have no floodplain regulation measures, such as a reservoir, could induce development onto the floodplain thus increasing the amount of damageable property and altering the stage-damage

function.

3/ Levees or channel modifications which reduce channel storage will probably not have an appreciable effect on the discharge-frequency relationships at their location, but could alter this relationship downstream.

SYSTEM FORMULATION

The major problem of system formulation is determining what combination of measures will produce the 'best' system. Three pieces of information can be useful in answering this question. First, information which provides an understanding of what each measure can do and under what conditions it is effective. This subject was discussed in the previous section. Second, a strategy for formulation - a rational, systematic approach which is likely to yield a 'better' system than if the approach were not followed. Third, a means to assess the overall performance of each system so that a 'best' system can be selected. Formulation strategies will be discussed below and the subject of system performance in the section which follows.

Formulation Strategies

At the plan formulation stage a variety of information is available both about the problem, the capability of measures to reduce or eliminate the problem, about public preferences, institutional guidance, and cost sharing capability. This is all important information and will influence not only the formulation of alternative plans, but their selection. How to utilize this information in a rational, systematic manner is the question to which formulation strategies hope to provide answers. A variety of approaches have been used in the past. These are identified and discussed in reference 3. The discussion which follows will utilize the mathematical model approach as a means to formulate alternatives to achieve the national economic development objective. Specifically, this means using simulation

model HEC-5C to develop systems which maximize net economic benefits, the traditional surrogate criterion for national economic development(6). Although there are other approaches which do not use mathematical models for formulation, models are still useful for assessing a system's performance and HEC-5C has the capability of analyzing a system's hydrologic and economic performance regardless of the strategy used to develop the system.

The principle of maximization of net economic benefits is applied by computing for each system or measure the flood damages and costs with and without the measure. The economic benefit derived from inundation reduction is the difference in damages with and without the measure. The difference between the benefits and costs is the net economic benefit. The objective of a strategy using this principle is to identify the system of measures which maximizes the net economic benefit. Two strategies useful for achieving this objective are discussed below:

First Added Strategy

Given an existing system and an array of flood control measures which are to be considered as possible additions to the existing system this strategy proceeds as follows:

- · Compute the expected annual damages for the existing system.
- Add one of the flood control measures to the existing system and compute the expected annual damages.
- Subtract the expected annual damages with and without the flood control measure. (This difference represents the expected benefits of implementing the flood control measure.)

- Subtract the cost of the measure from the expected benefits, this difference is the net benefit.
- Remove the measure being considered from the existing system, add another measure to the existing system and repeat the computations. This procedure is repeated until all the measures being considered have been added individually to the existing system and their net benefits computed.
- That measure which provides the greatest net benefits (greatest positive value) is selected for inclusion in the existing system. This new system becomes the base system and the process is repeated by adding each measure one at a time, computing net benefits and selecting the next measure to be added. When no measures yield positive net benefits that is the system with maximum net benefits.

Table 1 contains information adapted from a recent study and illustrates this strategy. Flood control measures A-J are proposed for inclusion within the system. Measures A, C, and E have already been implemented. Stage 1 represents the 'first added' value of proposed measures. The incremental value (net benefits added) by measure F is the largest so it is selected for inclusion in the system. Stage 2 represents the 'first added' value of the measures with the base system now comprised of measures A, C, E, and F. Note that many of the values change because of system effects. Measure J is selected for addition to the system. The remainder of the table contains the analysis through to completion.

TABLE 1
FIRST ADDED FORMULATION STRATEGY

First Added Value (\$1000 per year) /					
deasure	Stage 1	Stage 2	Stage 3	Stage 4	Formulated System
A*					А
B	20	5	-2	-3	
C*	·				С
Э	16	16	16**	*=	c
£*		••			Ε
F	35**				F
G	-10	0	ŋ	n	
Ħ	6	-12	-12	-15	
I	-2	-2	-2	-2	
j	15	18**			J

^{1/}First added value is system net benefits with the measure added minus system net benefits without the measure added.

The name 'first added' is derived from the fact that each measure is considered as being the only or 'first' measure added to the existing or base system. The objective of this strategy is to identify that measure which will be the most help in reducing flood damages, add it to the existing system then seek out the next most effective measure and so on. Being able to identify the most effective measures is the advantage of this strategy. Unfortunately this is only a partial advantage. As measures are added the base system changes and a different base system may yield

^{*} Signifies existing system

^{**}Signifies system addition

different expected annual damages. For example, in Table 1 suppose that at stage 1 measure B was added instead of F, this would change the net benefits of all measures at stage 2 and perhaps 0 instead of J would yield the higher value. One might argue that it's improper to select B over F since F is a more effective measure. This would be correct if only one measure or a given level of damage reduction were sought, but as long as the sole criterion is maximization of net benefits it's the final system which is sought not the method by which one gets there. If by adding B before F in the strategy the final system included measures I and yielded more benefits then it would be a better system. The point is that one cannot be sure that by formulating a system using the 'first added' strategy the system with the maximum net benefits will result - there will always linger the feeling that there may be another combination of measures that may be better. In practice this problem may be more imaginary than real.

Last Added Strategy

As one might surmise from the name, this strategy considers all proposed measures added to the existing system and removes them individually one at a time, hence the name 'last added'. The procedure is as follows:

- Add to the existing system all proposed measures and compute the expected annual damages.
- Remove one of the measures from the system and compute the expected annual damages.
- Compute the difference in expected annual damages with and without the measure. This is the expected annual benefit of implementing the measure, i.e., adding it to the system.

- Subtract the cost of the measure from the expected benefits, this difference is the net benefits of adding the measure.
- Add the measure back into the system and remove another measure and repeat the computations. This procedure is repeated until all measures have been removed individually from the system and their net benefits computed.
- That measure which provides the least net benefits (greatest negative value) is removed permanently from the system. This new system becomes the base system and the process is repeated by subtracting each measure one at a time, computing net benefits, and selecting the next measure to be deleted. When all measures exhibit positive net benefits that is the system with the maximum net benefits by this strategy.

Table 2 contains information adapted from a recent study and illustrates the strategy. Flood control measures K through T are candidates for inclusion within a system. Measures L, P, and R have already been implemented. Stage I represents the 'last added' value of the measures. The incremental value (net benefits) lost by adding measure Q in the last position is the greatest (-30) so it is selected for deletion from the system. Stage 2 represents the 'last added' value of each measure with the base system now excluding component Q. Note that a number of the values have changed because of system effects. Measure K is selected for deletion. The remainder of the table contains the analysis through to completion.

TABLE 2

LAST ADDED FORMULATION STRATEGY

	_	Last Added	P 9 A A		
<u> leasure</u>	Stage 1	Stage 2	Stage 3	Stage 4	Formulated System
K	-20	-10**	••	••	
L*					L
M	10	0	-4**		
8	6	6	6	8	:1
Ü	3	S	3	12	0
P★					P
Q	-30**			••	
R*					R
S	0	- 6	12	10	\$
T	-2	ŋ	0	2	T

Last added value is system net benefits with the measure in the system minus system net benefits without the measure added.

The 'last added' differs from the 'first added' strategy by the base system which is used to build upon and by its basic objective.

The 'last added' begins with the existing system plus all proposed measures; the 'first added' begins with the existing system. Because each strategy will result in the formulation of different combinations of measures each strategy could arrive at a different system. However, as was mentioned in connection with the 'first added' strategy the realities of using other information and approaches in formulation, and the

^{*} Signifies existing system.

^{**}System measure that is dropped.

gap between authorization and appropriation may minimize any significant differences. The 'last added' strategy does, however, introduce some complexities to the analysis where more than one measure at a location affects the same hydrologic or economic relationship. In this situation caution must be exercised to insure that the proper hydrologic and economic relationships are used. For example, a levee project has associated with it a particular stage-discharge relationship. Similarly, a channel modification project creates a unique stage-discharge relationship. When both are considered as alternative measures at the same location it would be necessary to develop a combined stage-discharge function when both are included in the 'last added' strategy. When one measure is removed the combined function would be replaced by the function for the measure remaining. A similar problem develops when considering flood proofing and relocation as alternative measures. If both are added to the system. as would be required for the 'last added' strategy, one may be redundant. For example, if all damageable property were removed there would be no need to flood proof. If, however, only a few structures were relocated and the remainder flood proofed both measures could be included provided a combined stage-damage function were developed. Combining relationships and avoiding redundant measures is not necessary when using the 'first added' strategy since each measure comes into the system one at a time.

While the objective of the 'first added' is to find the most effective measure to add, the objective of 'last added' is to find the least effective measure to delete. A reasonable strategy combining the two is

to apply the first and last added strategies through sufficient stages to identify those components that are obviously good, and to screen out those that are obviously inferior and zero in on the system to be selected by analyzing logical combinations of the remainder.

ASSESSMENT OF SYSTEM PERFORMANCE

Once alternative flood control systems have been formulated their performance should be assessed as the next step towards evaluation and selection. Assessment means an impartial, objective, factual display of the system performance. System performance refers to how a system functions. Whether this behavior is good or bad depends upon how it is supposed to function, and this in turn depends upon the purpose for which it was designed. The purpose of a flood control system is to reduce flood damages and its performance is measured by the extent to which this purpose is achieved and the manner by which it is achieved. Several measures of performance are described below and summarized on page 26.

Degree of Protection and Risk

Degree of protection is a measure of the hydrologic effectiveness of a system, expressed as the exceedance interval of the event that can be controlled to nondamaging flows. For example, 50-year protection means that, at a specific location, the peak flow of a flood with an exceedance interval of 50 years is not expected to exceed the nondamaging channel capacity at that location. Theoretically the flood peak and nondamaging

channel capacity are just equal; thus a flood with an exceedance interval of 51 years would exceed the nondamaging flow. It is important to recognize that degree of protection is associated with a specific location and discharge-frequency relationship. It is tied to location in the sense that it measures the protection, at a particular damage center, provided by measures either at that location or at other locations in the basin. It depends upon the discharge-frequency relationship because it is from this relationship that the exceedance interval is determined; and the frequency relationship itself is developed for a specific location.

Often the procedure for developing the modified function is to select hydrologic events with peak flows over the range covered by the unregulated frequency curve. The system's response to each event is then simulated and the resulting modified peak flow determined. Assuming the same exceedance frequency as the unregulated flow the regulated flow is then plotted to produce a modified frequency curve. Centering an event where a particular flood control measure will be effective in reducing peak flow will produce a different modified curve than if the centering were in a part of the basin where the measure could not be effective. Therefore, care must be exercised when selecting the events to be simulated so the relationship is as unbiased as possible. This is more a problem for large basins where the geographic differences between centerings can be large, than for small basins where there is less latitude for centering. Once a modified discharge-frequency relationship is developed the degree of protection is determined by finding the exceedance

interval for the nondamaging flow. The degree of protection for unregulated or existing conditions can be determined in the same manner using the appropriate frequency relationship.

Risk is defined as, "the probability that one or more events will exceed a given flood magnitude within a specified period of years." How does this differ from exceedance frequency and degree of protection? Both exceedance frequency and degree of protection, in their normal usage reflect the probability of an event being exceeded during any one year. Risk on the other hand usually refers to a probability not in any one year, but in some other specified time period. For example, to say a location has a 100-year level of protection is also to say that there is a 1% (1/100 year) chance that a flood will exceed that given level of protection during the next year. Or, put another way, there is a 1% risk. However, if instead of any one year we want to know the risk or percent chance of exceedance during the next 30 or 50 years, these values are 25% and 40%, respectively (see the data on next page). The graph on page 24 shows in graphical form the percent risk of one or more flood events being exceeded for a range of annual exceedance frequencies and periods of time. Risk is important as a hydrologic effectiveness criterion because it reflects the higher probability associated with a period longer than next year. And this is important because it conveys a more realistic picture of probable future conditions.

Estimated Risk*
Exceedance Frequency = 1% Annually

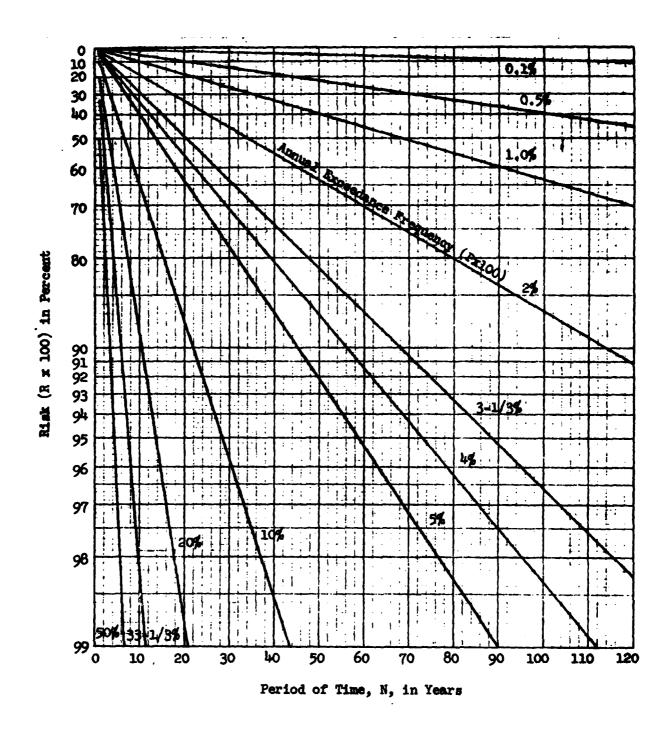
Period of Time In Years	Risk (in nercent) One or Hore Events	
30	26	
50	49	
70	50	
100	63	

^{*}From Appendix 10, "A Uniform Technique for Determining Flood Flow Frequencies (Draft)," U.S. Water Resources Council, 3 December 1974.

When assessing system performance using degree of protection or risk criterion the effectiveness of alternative measures or systems is determined by comparing these criterion at each location with each measure. While it is not likely that one degree of protection or one percent risk can be assigned to the system as a whole, it is still useful to assess effectiveness by looking at each location within a system. Used in this way degree of protection and risk provide a useful hydrologic criterion to complement the economic measures of performance.

Damage Reduction

Damage reduction is a measure of economic effectiveness, usually expressed as the actual dollar value of the difference in expected annual damages with and without proposed flood control measures or as a percentage of the total expected annual damages. Expected annual damages are computed as described previously and the reduction represents the flood control benefit of the measure or system being considered. As a measure of performance it tells how well a measure or group of measures is achieving



RISK OF ONE OR MORE FLOOD EVENTS EXCEEDING
A FLOOD OF GIVEN ANNUAL EXCEEDANCE FREQUENCY WITHIN A PERIOD OF YEARS

From Appendix 10, "A Uniform Technique for Determining Flood Flow Frequencies (Draft)," U.S. Water Resources Council, 3 December 1974.

its intended purpose, i.e., reducing damages caused by flooding. Because this reduction is expressed in average annual terms it is representative of the average damages likely to occur over a full range of hydrologic events.

Benefit-Cost Ratio

The most common measure of economic efficiency is the benefit-cost ratio, that is, dollar benefits per unit cost. As a measure of system performance it represents the capability of a system or measure to achieve its desired purpose (reduce flood damages) with a given amount of resources (capital, 0&44 and replacement costs). It is computed by dividing the total reduction in damages by the total cost of those measures required to achieve that reduction. Unlike damage reduction alone the benefit-cost ratio accounts for cost. This is important because it indicates how much must be committed to obtain that level of economic performance.

Het Benefits

Another measure of economic performance is net benefits. Usually expressed as average annual dollar benefits minus average annual dollar costs. In flood control planning it is an economic objective of formulation to maximize the net benefits. Flood control measures are added as long as each measures net benefits are positive, or alternately the incremental benefit-cost ratio is positive. This insures a benefit-cost ratio equal to or greater than one (the minimum acceptable level of efficiency). Het benefits complement the other two economic performance criteria, damage reduction and benefit-cost ratio; damage reduction being

a measure of the expected reduction in economic loss, benefit-cost ratio the measure of economic efficiency and net benefits the total dollar contribution of the plan.

TABLE

Summary of System Performance Criteria

<u>Criteria</u>	<u>l'nits</u>	<u> leasures</u>
Degree of Protection	exceedance interval, years	hydrologic effectiveness
Risk	percent chance	hydrologic effectiveness
Damage Reduction	average annual dollars	economic effectiveness
Benefit-Cost Ratio	dollar benefits per dollar cost	economic effectiveness
Het Benefits	average annual dollars	economic effectiveness

REFERENCES

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- 4. U.S. Army, Corps of Engineers, Engineering Circular 1105-2-12, "Evaluation of Economic Renefits for Flood Control and Related Water Resources Planning," 28 June 1974.
- 5. Hagen, Vernon K., "Formulating Flood Control Capability of Water Resource Projects," in Proceedings of a Seminar on Hydrologic Aspects of Project Planning, The Hydrologic Engineering Center, U.S. Army, Corps of Engineers, March 1974.
- 6. U.S. Army, Corps of Engineers, Engineering Pamphlet 1165-2-1, "Digest of Water Resources Policies," January 1975, page A-35.

PART II

FALL RIVER: AN EXAMPLE USING HEC-5C

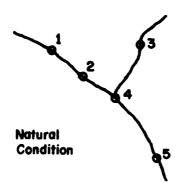
If it were desired simply to provide flood protection at a single location and assess the performance of alternative measures, computer simulation may not be necessary. But where many locations are involved and these locations are interrelated such that what happens at one location influences another, then computer simulation can make a significant contribution to both formulation and assessment. PEC-5C is a simulation model which simulates the operation of flood control systems and can accommodate all of the flood plain management measures discussed previously. It has the capability to compute net benefit information for use with the 'first' and 'last added' formulation strategies. Once formulated, a system's performance can be assessed using hydrologic and economic information output by the model.

To illustrate the use of the program, the Fall River System shown on the next page will be used. In its natural (unregulated) condition, flooding caused extensive flood damages in the vicinity of control point 4. To reduce flood damages, two reservoirs have been constructed in the basin at control points 1 and 3. Although they have been effective in reducing damages, flooding still occurs and an array of measures are being investigated to help reduce the remaining flood hazard. Each of these systems - natural (unregulated), existing, and those with proposed measures will be analyzed using HEC-5C. A brief discussion of the input data cards

required to model each condition and some of the output results are contained in the text. Appendix I contains selected output.

viatural (Unregulated) Condition

A major storm which occurred 5-10 June 1952 was selected from hydrologic records to be representative of major flood events. Local inflows to the river resulting from this storm were computed at five control points using unit hydrograph techniques. Table 1 summarizes the results in 6-hour time periods. Also, shown in Table 1 are channel capacities and routing criteria for the river system. Figures 1 and 2 show the stage-discharge and discharge-frequency relationships for control point 4, also developed from hydrologic studies.



Damage surveys in the vicinity of control point 4 were conducted in 1952 and have been updated periodically. A stage-damage relationship for control point 4 is shown in Figure 3. Expected annual damages are computed by combining the stage-damage and stage-discharge relationships into a discharge-damage curve (Figure 4), combining this with the discharge-frequency curve to obtain the damage-frequency relationship

(Figure 5) and then integrating under the curve. These data are presented in tabular form in Table 2.

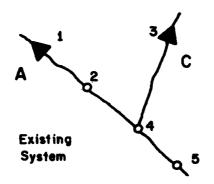
All necessary data to simulate the river system in its natural condition has been developed. These data are arranged according to the input format for NEC-5C. Input data and the simulation output are shown in the Appendix I, pages 2 through 15. Because of a requirement in the HEC-5 program that the control point furthest upstream be a reservoir, it is necessary to put in a dummy reservoir at control points 1 and 3. Thus, two sets of reservoir cards RL, RO, RS, and RQ are included to represent these reservoirs. Since they store no water, they have no effect on the system.

Only the simulation results for flood number 2, ratio 1.0, are shown in the output data. The other flood ratios .3, 1.5, 2.0, 3.0 and 4.0 were computed and printed out, but are not included to keep Appendix I brief.

Results of the simulation indicate that expected annual flood damages for the base (natural) condition are \$1,721,300 (Appendix I, page 12). Since there were no modifications, there is no reduction in damage and all damages result from uncontrolled runoff. The maximum (6-hour average) flow occurring at control point 4 is 194,036 cfs (Appendix I, page 9) for flood 2. The nondamaging channel capacity is 35,000 cfs. From the frequency plot for control point 4 the exceedance interval for the non-damaging flow is approximately 1 year.

Existing System (Reservoirs A and C)

The sketch below shows the Fall River system with flood control reservoirs located at control points 1 and 3. This is the system as it now exists. To simulate the system operation, information is needed about reservoir storage levels, outlet capacity, and operating criteria. A summary of this information is tabulated in Table 3. Input cards J1, J2, RL, RO, RS, RQ and ID are used to carry the data required to describe the two reservoirs. Appendix I, pages 16 through 28, shows both input and output data under this condition.



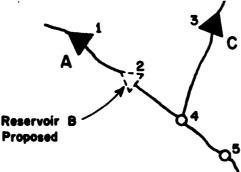
Adding two reservoirs to the natural system results in regulating the river flow below the reservoirs. Local inflow below the reservoirs, however, still remains uncontrolled. A 10% contingency allowance is made for forecasting streamflow two time periods in advance. These data are shown in fields 2 and 3 of the J2 card. The effect of regulation on the basic curves used to compute flood damages is to modify the discharge-frequency curve at all downstream control points. This modified curve is computed internally in the program using results from several simulations for a range of selected flood ratios. See Appendix I, page 27, for

a printer plot of these data. The nondamaging flow is still 35,900 cfs, and from the modified frequency plot the degree of protection is now approximately 2 years.

Simulation results show expected annual flood damages at control point 4 of 5696,320 with the two reservoirs (Appendix I, page 28). This is a reduction in damages from natural conditions of \$1,024,470. Uncontrolled local flow causes an expected \$525,750 in annual damages. For flood 2 the maximum flow occurring at control point 4 is 92,483 cfs (Appendix I, page 23). This is a substantial reduction (101,548 cfs) over unregulated conditions.

Reservoir D at C.P. 2

A reservoir is proposed for control point 2, shown below, as a means to further reduce flood damages at control point 4. The storage, outlet capacity, and operating criteria of Reservoir B were obtained from preliminary design studies and are tabulated in Table 4. The major effects of Reservoir B are to control local runoff between control points 1 and 2, and to store water above the capacity of Reservoir A. This modifies the discharge-frequency relationship at control point 4, and further reduces flood damages.



To simulate the system with Reservoir B added, it is necessary to input at control point 2 the reservoir information shown in Table 4. This is done by using the RL, RO, RS, and RQ cards. The ID card is modified to indicate that a reservoir exists at control point 2. Since any reduction in potential damages brought about by the reservoir must be computed as a reduction from damages anticipated under existing conditions, the damages remaining with the existing system - 3696,320 - are input using the DB card. Appendix I shows the specific input changes.

Tabulated on Table 5 are cost data for Reservoir B and other flood control measures. These data are input using the R\$ card for the capital cost, and the CP card for the percentage of the capital cost estimated for operations and maintenance. The capital recovery factor is also input using the CP card.

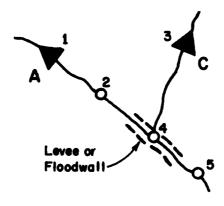
Results of the simulation show expected annual flood damages with Reservoir B in place to be \$214,550 (Appendix I, page 42). This is an annual reduction of \$482,270. Flood condition number 2 results in a maximum average 6-hour flow of 34,000 cfs at control point (Appendix I, page 36). The degree of protection with Reservoir B is between 10 and 15 years as determined from the modified frequency relationship at the nondamaging flow of 35,000 cfs.

Levee or Floodwall

Another alternative measure is to provide local protection in the form of levees or floodwalls along the main river channel in the vicinity

of control point 4. The primary hydrologic effects of levees or floodwalls is to increase non-damaging channel capacity by raising the channel sides, and to alter the routing criteria in the vicinity of the modification.

This results in a change to the stage-discharge, stage-damage, and discharge-damage relationships at the control point.



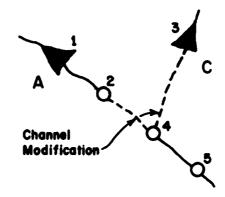
In the simulation model, increased channel capacity is taken into account by changing the maximum value specified on the CP card. The change to the stage-damage relationship may be handled in either of two ways. The first is to specify a <u>design</u> discharge on the C\$ card corresponding to the maximum nondamaging stage (Figure 6 and 7). No damages would be computed below this value. The second approach is to input on the DC cards, a modified discharge-damage relationship showing zero damages below the nondamaging discharge (Figure 8). Taking this latter approach, two sets of discharge-damage functions - one base condition, one modified condition - are prepared as input. This is shown in Appendix I, page 44. In this example, the routing criteria and stage-discharge relationship were not modified to account for the change in river cross-section because it was

assumed the levee or floodwall would not extend very far either upstream or downstream of control point 4; hence, the hydrologic effect would be small. If it were desired to change these functions it would be necessary to develop storage-outflow relationships for the reach, or based upon experience with similar levee or floodwall measures, make an estimate of what this new criteria might be. Thether or not this would be worthwhile depends upon the extent of the change and the level of detail desired in the study.

The simulation results indicate expected annual damages were reduced \$441,000 (Appendix I, page 56) and that there will remain \$255,020 in damages. The maximum 6-hour flow for flood 2 at control point 4 was 119,411 cfs (Appendix I, page 51). The degree of protection would be 30-40 years and the nondamaging channel capacity 237,000 cfs.

Channel Modification

Modification of the existing channel between control points 2, 3 and 4 offers another way to reduce flood damages. This measure includes cross-section enlargement, straightening, and clearing and snagning. The objective is to increase the channel carrying capacity to pass the same flow at a lower stage, or alternately, to pass a greater flow at the same stage. The hydrologic effects of channel modifications are similar to those caused by levees and floodwalls - increased nondamaging channel capacity, modified stage-discharge relationship, and modified routing criteria.



Increased channel capacity is input into the simulation model using the CP card. The change in the stage-discharge (Figure 9) relationship caused by an enlarged channel cross-section must be computed external to the model then combined with the stage-damage relationship (Figure 3) to produce modified discharge-damage data (Figure 17). These data for the modified relationship are then input using a second set of DC cards for corresponding values on the DQ cards. It was estimated that the channel modification would change the Huskingum X from X = 0.3 to X = 0.1 and K from 6 hour to 5 hour for reaches 2 to 4 and 3 to 4. (A more accurate estimate of routing effects could have been made by computing storage—outflow curves for natural and modified conditions using backwater techniques, and then using the Modified-Puls channel routing method.) The nondamaging channel capacity at control point 4 would be 65,000 cfs.

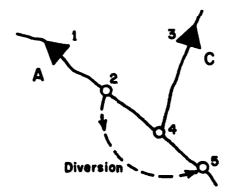
These changes are reflected on the RT and CP cards.

Results shown in Appendix I, page 70, indicate that expected annual damages were reduced \$271,640 due to channel modification. Damages remaining amount to \$425,100 on an average annual basis. The maximum flow at

control point 4 for flood 2 was computed as 91,201 cfs (Appendix I, page 65). Degree of protection is approximately 5 years for a nondamaging flow of 65,000 cfs.

Diversion

Frequently, where the topography is flat and relatively large areas are available to store water temporarily, flow is diverted from the main river around a potential damage center, to re-enter at some point downstream. This measure is illustrated in the sketch below. Flow is diverted at control point 2, routed to control point 5 where it re-enters the main channel. The obvious hydrologic effect is to reduce the peak discharge at location 4 which results in a modified discharge-frequency curve at control point 4 and a corresponding reduction in damages. The amount of this reduction depends upon the amount of water diverted.



To account for this measure it is necessary to input into the model the locations where flow is being diverted and returned, the rate of diversion and return flow, and the routing criteria by which the diversion

flow is to be routed. In this example, the magnitude of the diversion varied as a function of the streamflow as shown below:

Control Point 2

Streamflow	0	30,000	50,000	70,000	90,000	110,000
Diversion		0	22,000	37,500	45,000	51,000
Streamflow Diversion		130,000 55,000		150,000 58,500		,000 ,500

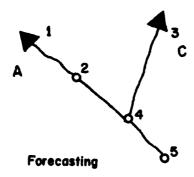
These data were input using the QS and QQ cards at control point 2 (see Appendix I, page 72). It was also determined that 90% of the flow would return to the main channel at control point 5, and that the diversion flow would be routed between control point 2 and control point 5 using a Muskingum X = .15, K = .24 hour and four subreaches. Both of these criteria are input using the DR card at control point 2. The modified discharge-frequency relationship at control point 4 is computed internally by the model using the flood ratios selected earlier (Appendix I, page 83). The degree of protection from this modified curve is approximately 3 years for a nondamaging flow of 35,000 cfs.

Output from the simulation indicates expected annual flood damages were reduced \$278,370, and \$417,950 in expected damages still remain (Appendix I, page 84). The maximum flow at control point 4 is 53,770 cfs during flood number 2 (Appendix I, page 79).

Flood Forecasting

Flood forecasting is intended to provide advance information about rainfall and runoff conditions to assist in more efficient operation of

a flood control system. Hopefully, this advance information will help to minimize flood damages. The usual means of forecasting is with a network of monitoring stations feeding rainfall-runoff data into a central operations center. These raw data are used in analyses to forecast future system conditions. The principal effect of such a system is hydrologic - better data yields better system operation which in turn reduces flooding at damage centers.

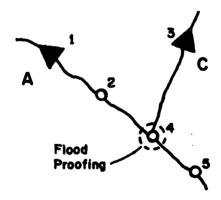


In the Fall River Dasin operation of the existing system (Reservoirs A and C) assumes that flood discharges are known two 6-hour periods in advance with a 10% contingency allowance for local flows. To illustrate the effect of a flood forecast system it is assumed that the discharges are known six periods or 36 hours in advance with a 15% contingency factor. This information is input to MEC-5C by simply changing the contingency factor in field 2 and the forecasting period in field 3 of the J2 card (Appendix I, page 36). Results of the system simulation indicate expected annual damages are reduced \$22,850. Damages remaining are 3673,970, Appendix I, page 98, and the magnitude of flood peak is modified for each period (Appendix I, pages 90-91). The degree of protection

exceeds the protection provided by the existing system, although this does not have to be so, but depends upon the magnitude of the change in flow brought about by the forecasting.

Flood Proofing

Flood proofing has the effect of reducing damages below the upper limits of the flood proofing materials. Thus, flood flows below this elevation can be expected to cause limited or no damage; above this elevation expected damages will remain essentially unchanged from conditions without flood proofing. Since this measure is structure specific, the magnitude of the damage reduction depends upon the degree of flood proofing provided specific structures, and the aggregation of all structures. This change results in a modified stage-damage relationship (Figure 11) which produces a modified discharge-damage function (Figure 12) and damage-frequency curve. There is no hydrologic effect of flood proofing unless alterations are made to the flood plain which affect the cross-section of flood flow.



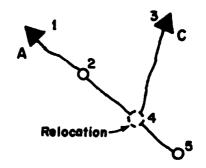
To account for flood proofing in the model it is only necessary to input the modified discharge-damage data (Figure 12). This can be done

by using another set of DC cards. The first set is input to compute expected annual damages under natural conditions. Input changes are shown in Appendix I, page 190.

Output from the simulation shows an expected annual damage reduction of \$233,140 with \$463,630 remaining (Appendix I, page 112). The maximum flow at control point 4 with flood number 2 is 92,483 cfs (Appendix I, page 101). The degree of protection with flood proofing is the same as with the existing system, approximately 2 years, since the measure does not affect the nondamaging flow at control point 4.

Relocation

A direct way to reduce flood damages at control point 4 is to relocate damageable structures out of the flood plain. This relocation results in modifying the stage-damage relationship as shown in Figure 13. This curve represents the situation where structures near the river are relocated out of the flood plain, but structures further away remain, thus the damages are reduced by the value of only those structures removed. When the modified curve is combined with the stage-discharge curve (Figure 1) a modified discharge-damage relationship results (Figure 14). The hydrologic effect of relocation is generally small, but could be significant if major flow obstructions were removed, in which case the channel capacity and routing criteria should be modified.

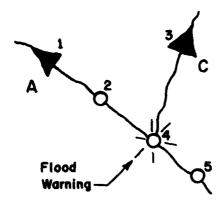


The change in stage-damage data is input into the model by modifying the discharge-damage function. This is accomplished by using a second set of DC cards to reduce damages at lower stages. Appendix I, page 100, shows the cards used. Note that the nondamaging flow is 180,000 cfs.

Simulation results indicate expected annual damages are reduced by \$416,750, with \$280,070 remaining (Appendix I, page 126). Since there is no hydrologic effect the magnitude of the flow at control point 4 remains unchanged from the existing system - 92,488 cfs. The degree of protection is approximately 20 years.

Flood Harning

Flood warning allows action to be taken to protect or remove damageable property. Uhile flood forecasting is associated with gaining advance information for better system operation, flood warning is associated with advance information for protecting property. The principle effect is economic in that the stage-damage function is altered by lowering potential damages when a warning is effective.



At control point 4 in the Fall River basin it is assumed that a warning system can be implemented and property protected or removed above flood stage. The discharge-damage relationship is modified by assuming a 50 reduction in damages at every flood stage. The new damage data is input to NEC-50 using a second set of DC cards.

The simulation output shows a reduction in damages of \$35,190. There is no reduction in flow at control point 4. The degree of protection is the same as for the existing system.

System Formulation and Assessment

Because of the simplicity of the Fall River system, it is difficult to illustrate all the principles of system formulation discussed in part I.

Table 6 summarizes damage, cost and benefit information at control point 4 for each measure. The net benefits represent the net benefits in the first added position. Using the first added strategy, relocation would be selected as the measure contributing most (maximum net benefits) to national economic development and thus, using economic criterion alone, would be added to the existing system. To move to the second stage using this strategy it would be necessary to modify the stage-damage and discharge-damage functions at control point 4 to reflect the annual S416,750 reduction in damage brought about by the relocation. The new system which includes relocation would then be simulated, damages remaining computed, and each measure added one at a time. This was not done in this example because it was obvious that damage reduction from relocation was sufficiently

large that none of the remaining measures in the 'first added' position could produce positive net benefits. Thus, it was only necessary to complete the first stage computations to make a decision.

The 'last added' strategy is difficult to apply to the Fall River example because all measures except the reservoir at control point 2 and flood forecasting occur at control point 4. This requires that a combined stage-damage and stage-discharge relationship be developed with all measures and with each measure deleted. This is no small taks.

The economic performance of all measures is also summarized in Table 5. The most effective measure is a reservoir at control point 2. It is most effective because it does the best job of reducing flood damages - \$432,270. However, it is highly inefficient from the economic standpoint. A very large amount of capital is required to construct the reservoir and as a result the net benefits are negative. Flood warning is the most efficient measure, yielding the greatest dollar benefit per dollar invested - 3.23. Using economic criterion alone the measure which would be added to the existing system would be relocation, not because it is most effective (damage reduction) or most efficient (B/C), but because it adds the most to the national economic development account - \$131,950. Each assessment gives a somewhat different perspective of performance, and together help to describe a measure's total performance in economic terms.

Table 7 presents a summary of the hydrologic performance of each measure in terms of its expected degree of protection. A range of

protection is given because none of the flood ratios were controlled to just the nondamaging flow. As shown a levee or floodwall yields the greatest protection for any single measure.

TABLE 1
HYDROLOGIC INFORMATION
Natural Condition

Control Point Inflows*- June 5-10, 1952 STORM

Date	Time	Inflow to C.P.1 (cfs)	Inflow C.P.1 to C.P.2 (cfs)	Inflow to C.P.3 (cfs)	Inflow C.P.2,3 to C.P.4 (cfs)	Inflow C.P.4 to C.P.5 (cfs)
5 Jun	2400	1,000	2,000	3,000	2,000	1,000
6 Jun	0600	2,000	3,000	6,000	4,000	2,000
	1200	3,000	4,000	27,000	19,000	9,000
	1800	18,000	6,000	60,000	13,000	6,000
	2400	37,000	20,000	105,000	10,000	5,000
7 Jun	0600	42,000	57,000	78,000	7,000	3,000
	1200	50,000	100,000	60,000	4,000	2,000
	1800	27,000	90,000	45,000	1,000	500
	2400	20,000	70,000	33,000	1,000	500
8 Jun	0600	13,000	50,000	24,000	4,000	2,000
	1200	5,000	37,000	18,000	10,000	5,000
	1800	4,000	24,000	12,000	25,000	12,000
	2400	3,000	24,000	12,000	13,000	6,000
9 Jun	0600	2,000	15,000	9,000	7,000	4,000
	1200	1,000	9,000	6,000	4,000	2,000
	1800	1,000	3,000	3,000	2,000	1,000
	2400	1,000	2,000	2,000	1,000	500
10 Jun	0600	1,000	1,500	1,000	500	200

^{*}Average inflow for the period.

Control Point Hydraulics

	C.P.1	C.P.2	C.P.3	C.P.4	C.P.5
Channel Capacity (cfs)	6,000	21,000	12,000	35,000	37,000

Routing Criteria All Reaches

Muskingum Routing

At = 6 hours K = 6 hours X = .3

TABLE 2

ECONOMIC INFORMATION
Control Point 4, Unregulated Conditions

Exceedence Frequency	Stage (ft)	Discharge (cfs)	Damages
.999	3.6	28,800	0
.900	4.0	35,000	0
.800	4.3	42,000	\$ 180,000
.700	4.5	50,500	380,000
.600	5.5	60,500	500, 000
.500	5.8	73,000	630,000
.400	6.4	90,000	900,000
.300	7.2	114,000	1,250,000
.250	7.7	130,000	1,500,000
,200	8.2	150,000	1,930,000
.150	8.9	180,000	2,660,000
.100	10.0	230,000	5,000,000
.050	11.8	323,000	9,900,000
.020	14.5	490,000	12,220,000
.010	16.6	640,000	13,350,000
.005	18.9	840,000	14,150,000
.002	20.2	1,000,000	14,600,000

NOTE: See Figures 1 through 5 for a graphic display of these data.

TABLE 3

RESERVOIR INFORMATION - RESERVOIRS A AND C
Existing System

Reservoir Storage	Storage (ac-ft)		
	Level	A	<u>c</u>
Top of Surcharge	4	200,000	1,000,000
Top of Flood Control	3	150,832	755,408
Top of Conservation	2	50,000	100,000
Top of Inactive Storage	1	Ŏ	Ó

Reservoir Outlet Capacity

Keservoir A		Reserv	oir c
Storage (ac-ft)	Outlet Capacity (cfs)	Storage (ac-ft)	Outlet Capacity (cfs)
50,000	6,000	100,000	12,000
70,000	7,000	200,000	18,000
100,000	8,000	400,000	30,000
150,832	100,000	700,000	80,000
200,000	200,000	800,000	150,000
-	_ ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	1,000,000	500,000

Operating Criteria

- Two 6-hour periods of foresight on all inflows and local flows will be used in the system operation for all reservoirs.
- Below the top of flood control pool, reservoir releases will be made so as not to exceed the channel capacity at any downstream control point for which the reservoir operates. As soon as it can be determined (using assumed forecasting capability) that the reservoir will exceed the top of flood control pool, releases will be made equal to the channel capacity at the dam site. Above the top of flood control, releases will be made equal to inflow up to the maximum outlet capacity.
- The maximum rate of change of reservoir release is equal to the channel capacity at the dam site.
- There are no minimum flow requirements.
- Each reservoir will be operated for CP 4 only.
- A 10% contingency allowance is made for local flows for the 12-hour forecast period.

TABLE 4

RESERVOIR INFORMATION - RESERVOIR B Proposed Reservoir

Reservoir Storage

		Storage (ac-ft)		
	<u>Level</u>			
Top of Surcharge	4	1,000,000		
Top of Flood Control	3	654,576		
Top of Conservation	2	100,000		
Top of Imactive Storage	1	Ŏ		

Reservoir Outlet Capacity

Reservoi	r B
Storage	Outlet Capacity
(ac-ft)	(cfs)
100,000	21,000
200,000	30,000
400,000	40,000
600,000	100,000
800,000	300,000
1,000,000	500,000

Operating Criteria

- Two 6-hour periods of foresight on all inflows and local flows will be used in the system operation for all reservoirs.
- Below the top of flood control pool, reservoir releases will be made so as not to exceed the channel capacity at any downstream control point for which the reservoir operates. As soon as it can be determined (using assumed forecasting capability) that the reservoir will exceed the top of flood control pool, releases will be made equal to the channel capacity at the dam site. Above the top of flood control, releases will be made equal to inflow up to the maximum outlet capacity.
- The maximum rate of change of reservoir release is equal to the channel capacity at the dam site.
- There are no minimum flow requirements.
- Each reservoir will be operated for CP 4 only.
- A 10% contingency allowance is made for local flows for the 12-hour forecast period.

TABLE 5
COST INFORMATION

<u>Measure</u>	Capital Cost	Percentage O&M Cost of Capital Cost	Annual Average <u>O&M Cost</u>	Total Average Annual Cost*
Reservoir at CP 2	59,150,000	1.2	709,800	4,199,650
Levee or Floodwall	5,510,000	1.0	55,100	380,190
Channel Modification	3,420,000	2.0	68,400	270,180
Diversion	10,520,000	8.0	84,160	704,840
Flood Forecasting	120,000	1.6	1,920	9,000
Flood Proofing	3,480,000	0.7	24,360	229,680
Relocation	4,450,000	0.5	22,250	284,800
Flood Warning	100,000	5.0	5,000	10,900

*Discounted at 5-7/8%, 100 yr., capital recovery factor $(\frac{A}{p})$ = .059

TABLE 6
SUMMARY OF SYSTEM ECONOMIC PERFORMANCE

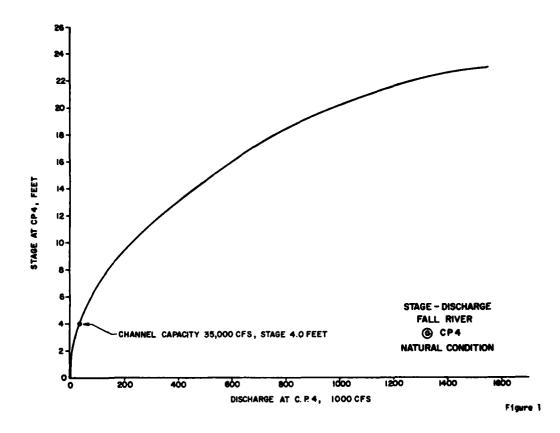
<u>Measure</u>	Annual Damage with Proposed Measure	Expected Annual Damage Reduction	Annual Cost*	Annual Net Benefit*	<u>B/C</u>
Existing System Reservoirs A and C	\$696,820	-	-	•	-
Reservoir at CP 2	214,550	482,270	4,199,650	-3,717,380	0.11
Levee or Floodwall	255,829	441,000	380,190	60,810	1.16
Channel Modification	425,180	271,640	270,180	1,460	1.01
Diversion	417,950	278,870	704,840	-425,970	0.40
Flood Forecasting	673,970	22,850	9,000	13,850	2.54
Flood Proofing	463,680	233,140	229,680	3,460	1.02
Relocation	280,070	416,750	284,800	131,950	1.46
Flood Warning	661,630	35,190	10,900	24,290	3.23

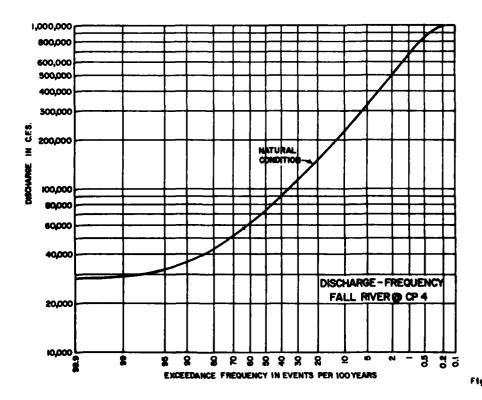
^{*}Discounted at 5-7/8%, 100 yr., capital recovery factor $(\frac{A}{\rho})$ = .059

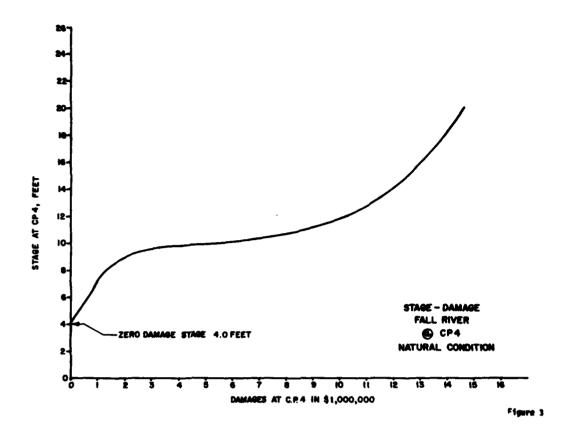
TABLE 7
SUMMARY OF SYSTEM HYDROLOGIC PERFORMANCE

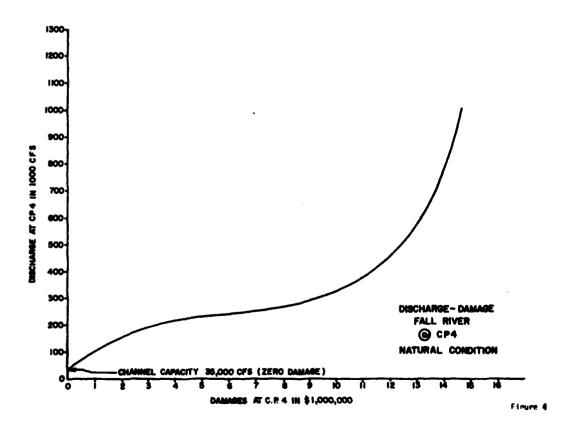
<u> Measure</u>	Nondamaging Flow at CP 4 (cfs)	Approximate Degree of Protection* (exceedance interval, years)	Risk of Nondamaging Frequency Flood Being Exceeded in Next 10 Years (percent chance)
Natural (Unregulated)	35,000	1	•
Existing System Reservoirs A and C	35,000	2	> 99%
Reservoir at CP 2	35,000	12	~ 56%
Levee or Floodwall	287,000	35	~ 26%
Channel Modifications	65,000	5	~ 89%
Diversion	35,000	3	> 98%
Flood Forecasting	35,000	3	> 98%
Flood Proofing	35,000	2	> 99%
Relocation	180,000	20	~ 40%
Flood Warning	35,000	2	> 99%

^{*}Obtained from interpolation between events with known frequencies (flood ratios) using the modified frequency curve computed and plotted for each measure.









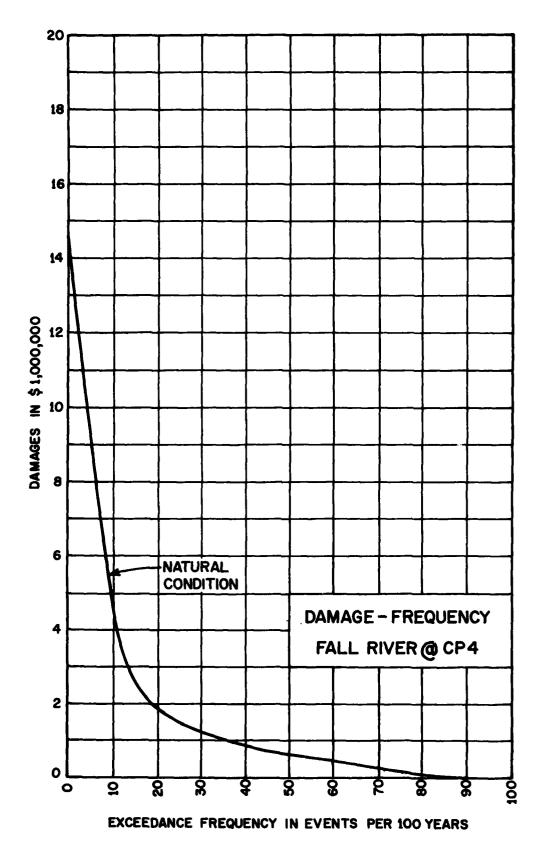
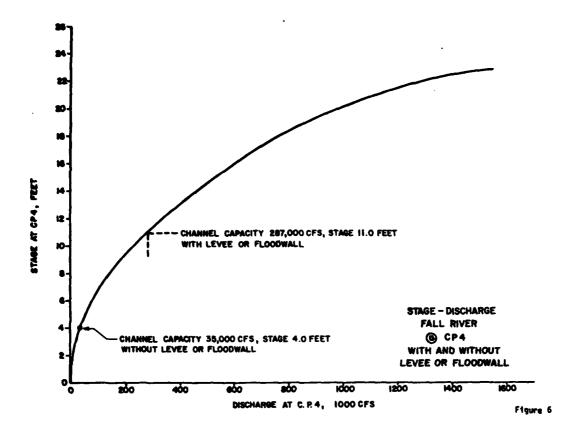
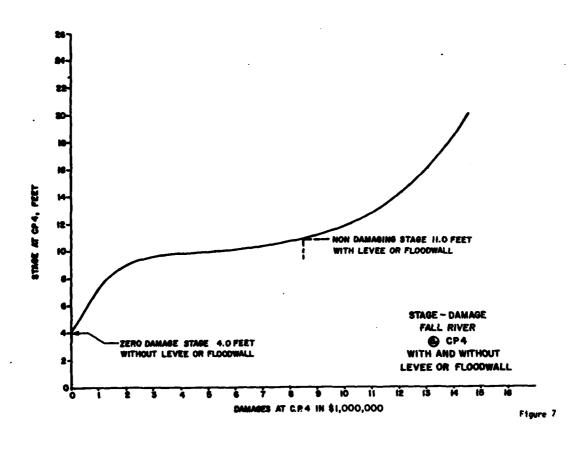
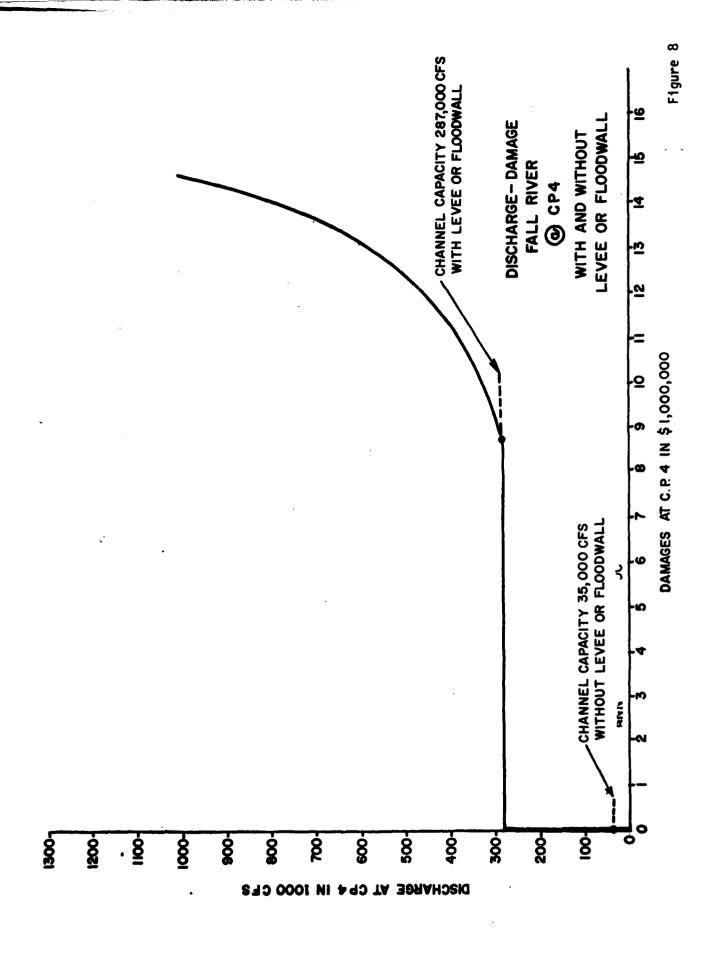
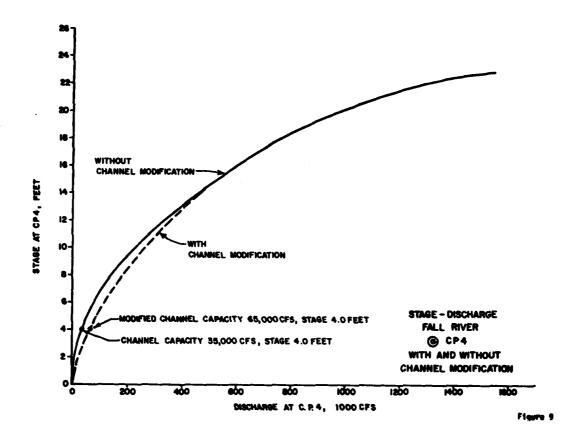


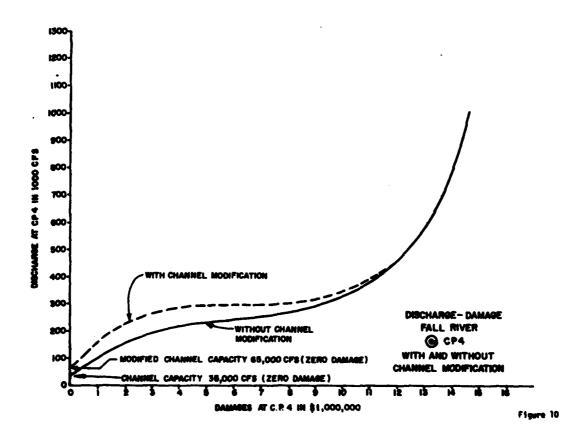
Figure 5

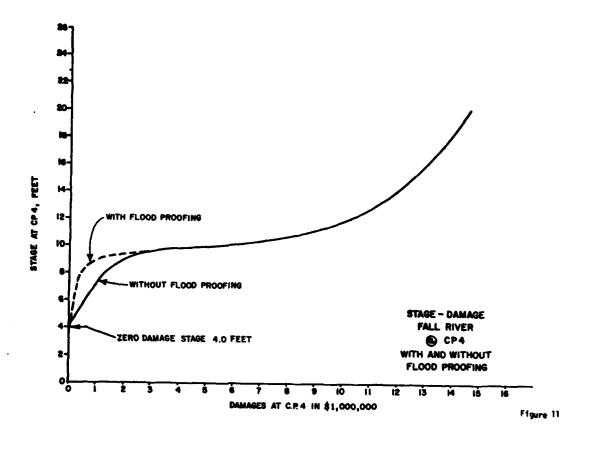


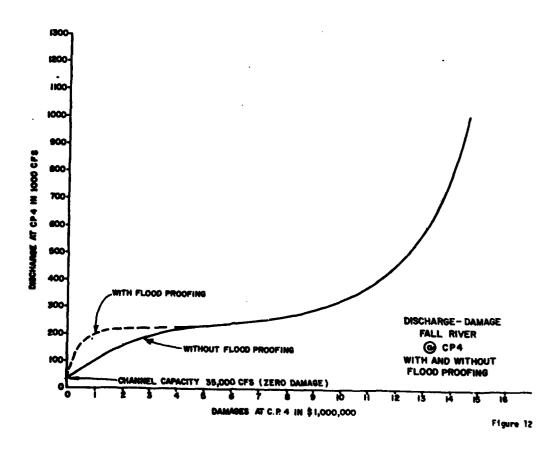


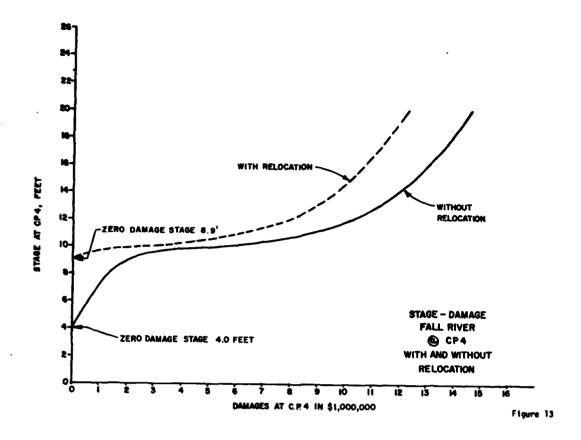


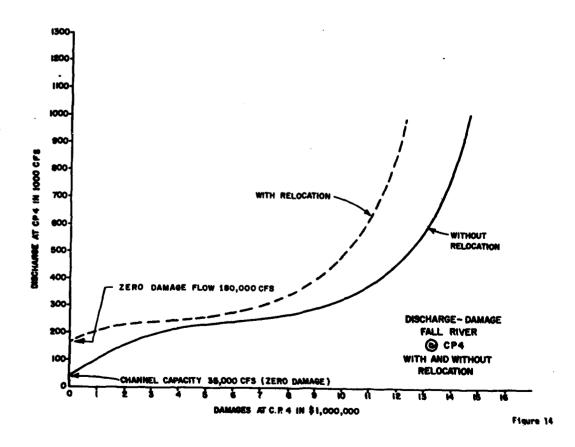


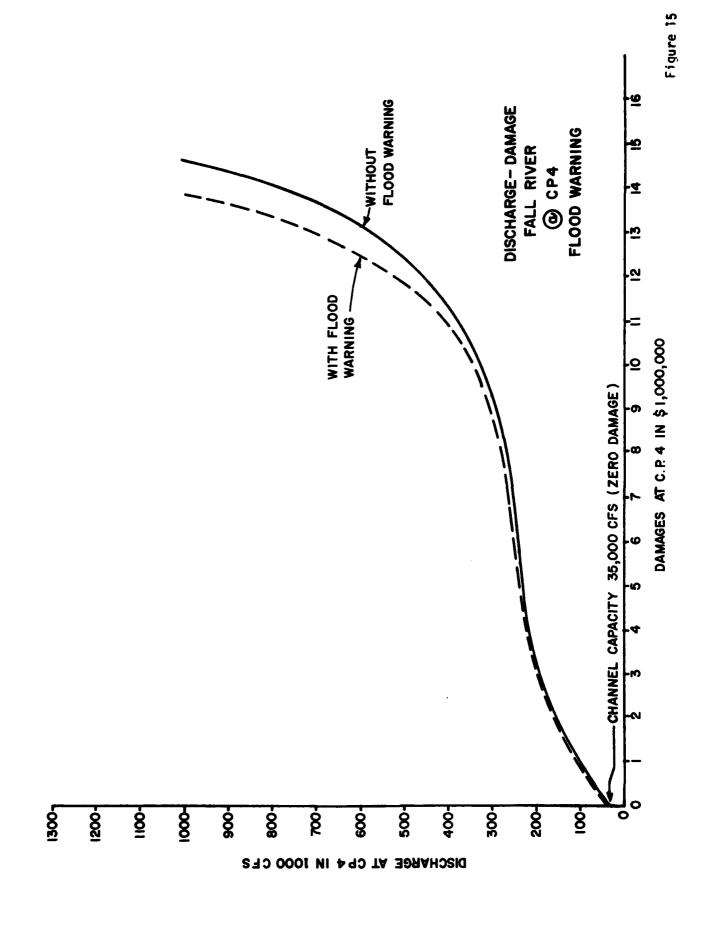












PART III

APPENDIX I

FALL RIVER BASIN

TRAINING DOCUMENT NO. 7

HEC-5C SELECTED OUTPUT

Contents

	<u>Page</u>
Foreword	1
Natural (Unregulated) Condition	2
Existing System (Reservoirs A and C)	16
Reservoirs B at CP 2	29
Levee or Floodwall	44
Channel Modifications	58
Diversion	72
Flood Forecasting	86
Flood Proofing	100
Relocation	114
Flood Warning	120

FOREWORD

The purpose of this appendix is to supplement the discussion on the analysis of structural and nonstructural measures by providing selected output from computer program HEC-5C. Detailed output from the program would be too voluminous to reproduce here for the many flood control measures being discussed, so only selected portions are included. The selected portions include, (1) input data used for the simulation, (2) hydrologic data at each control point for flood number 2, (3) a summary of hydrologic data for each flood ratio, (4) expected annual flood damage data at control point 4, (5) a discharge-frequency curve plot for the input and modified conditions, and (6) summary of economic costs and performance.

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PALL RIVER BABIN AND EXISTING SYSTEM (RESERVOIRS A AND C.) AND TABLES TO COMPUTE ANNUAL DANAGES FLOOD COPYS PLOOD RATIOS .S 1.6 1.5 2.6 3.6 4.6 USED TO COMPUTE ANNUAL DANAGES :

***** FLOOD NUMBER 1 *****

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# CP 2 10.012	1 JAIA SKIARAS	MAN REG D & FLO.PER MAN NAT D & PLO.PER MAN LOC D & D DV SATT & 1.007 48642 & 1.007 5000 B SATT & 1.000 27735 & 1.000	DOOD B 179% B SPIER DIDON F DERES DOO'N F DERISH	THE OTO MIN IN THE STREET AND THE STREET AND THE STREET ST	Second County 1,000 0735 C.175 1,003	150000 MAX 8YSTEM 6168 206166	***** FLOOD NUMBER 2 *****	THE STEAMS	MAX REG D & PLO.PER MAX NAT 0 + PLO.PER MAX LOC 0 + 0 BY RES + DES	0220 2 2.000 142140 1 2.000 0220 2 2.000 192016 2 2.000 0755 1 2.000 107651 2 2.010	R MIN 8TG MIN LEVEL WIPLD, PER IMAN ST8-MAN LEVEL & PLD, PER MAN REL CMAN CAP STORI	3 - 50000 - 2:000 + 2:011 - 120025 - 3:010 +2:015 - 0000: - 0000	2 100000 2,000 m 2,014 355557 . 2,356 m 2,665 12000 . 12000 100000	150000 WAX BYSTEM STGS seasse-	ARRES FLOOD NUMBER 3 seess	!	MAX PEG G . PLD. PER MAX MAT G . PLD. PER MAX LOC G . B
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LOC 3 RESERVOIR C (CP 5)	5,601 87EM 87Ge	104465 155949 H	Z. 007 4 5.01.	11 755406	2.000	21015	23.00	12000 1	00000
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POC 2 HEBENAGIN C (Ch. 2)	100.4	105950	2,000 + 6,006	761275	3.106 F	00.	136160	1 50001	00000
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EXPECTED ANNUAL PLOOD DANAGE SUMMARY CONTROL POINT NUMBER A

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HYDROLOGIC ENGINEERING CENTER DAVIS CA F/G 13/2 ANALYSIS OF STRUCTURAL AND NONSTRUCTURAL FLOOD CONTROL MEASURES--ETC(U) NOV 75 W K JOHNSON, D W DAVIS HEC-TD-7 NL AD-A106 700 UNCLASSIFIED 2×3

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FLOOD SUMMARY-EACH FLOOD COPYS 6062 12000 21000 12000 26767 1.006 2,004 5.005 1.004 2,112 0 1,005 2.003 2.034 4 2.031 * 2.811 + 2.292 + 2,353 . PLD. PER MAN REG G & PLD. PER MAN MAT G & FLD. PER 2.010 34600 & 2.006 194036 & 2.012 2.012 2.013 122016 2.000 a 1.000 117516 61274 300608 2,000 n 2,010 131746 2.000 + 2.013 205869 201304 710019 2,000 + 2,014 2,000 = 1,008 2,000 . 1,000 ARERS FLOOD NUMBER 5 SASES STATE FLOOD NUMBER 2 state PRESE FLOOD NUMBER 3 seess MAX SYSTEM STGS IN COST RESERVOIR R AT CP 2 COSTEM NO. 7 MAX BYSTEM STGS TAX REG 0 4 MAYOO 4 100000 50000 100000 250000 20000 250000 100000 100001 FLD.PLR 2,003 1.004 1.010 2.004 2,002 10.PER 3.012 3.013 1,018 HIN BYBTEH STGS MIN SYSTEM STGS ; | | | RESERVOIR 6 (CP 2) RESERVOIR C (CP 3) 1 RESERVOIR A (CP. 1) RESERVOIR C (CP 3) RESERVOIR A (CP 1) 2 RESERVOIR & CCP 2) RESERVOIRS RESERVOIRS 55 :: 203 304 200 200 22 200 22 3

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FLO.PLR MIN 876 MIN'LEVEL « FLO.PER MAX 876 MAX LEVEL « PLO.PER MAX REL CHAN CAP

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UNCONTROLLED LOCAL FLOW FLOOD DAMAGES

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MODIFIED DAMAGES DAMAGE REDUCTION

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Charmer.	SYSTEM ECOMONIC COST AND PERFORMANCE BUNNARY (EXCLUSIVE OF EXISTING SYSTEM COSTS)	SYSTEM CAPITAL	TOTAL SYSTEM ANNUAL OPERATING MAINTENANCE, AND REPAIR COST S S S 704,80	TOTAL SYSTEM ANNUAL COST as a a a a a a a second	AVERAGE ANNUAL DAMAGES . EXISTING SYSTEM	AVERAUE ANNUAL DAMAGES . PROPOSED SYSTEM 214,55	AVERALE ANNUAL DAMAGE REDUCTION	AVERAGE ANNUAL SYSTEM MET DAMAGE REDUCTION GENEFITS -3717,35				
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EXPECTED ANNUAL FLOOD DAMAGE SURMARY CONTROL POINT NUMBER 4

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SUMMARY OF SYSTEM'S EXPECTED ANNUAL FLUDD DAMAGES

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FALL RIVER BASIN *** FLOUD PROOFING ***
TRAINING DOCUMENT NO. 7
FLOOD RATIOS .3 1.0 1.5 2.0 3.0 4.0 USED TO COMPUTE ANNUAL DAMAGES

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Page 135 Flood Warning

FALL RIVER BASIN AAR PLUIDD WARNING AAA TRAINING ONCHWYT NG, 7 FLOND RAYINS .3 1.0 1.5 2.0 3.0 4.5 USED YN CHEPUTE ANNUAL DAMAGES

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